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14. ABSTRACT

An exploratory investigation has been made of transitional shock wave boundary layer interactions. In this case, the interaction is induced by a circular cylinder perpendicular to a flat plate. The tests were conducted in the Mach 5 blowdown tunnel of The University of Texas at Austin. The primary goal of this initial, exploratory study was to determine if repeatable transitional interactions could be generated. Measurements included surface flow visualization using the kerosene-lampblack technique and high speed schlieren imaging. Consistent with earlier experiments the current work shows that as the cylinder is shifted upstream on the plate and the interaction start moves into an area where the incoming boundary layer is transitional, rather than turbulent, the separated flow and overall interaction scales increase significantly. The separation location moves from about 2 cylinder diameters upstream of the cylinder in turbulent flow to about 4 diameters in transitional flow. Tests made on different days with the cylinder at the same station on the plate, within the region of transitional boundary layer flow, are highly repeatable. This is a very promising result. With repeatability ensured from test to test techniques such as PIV can be used with confidence in future studies to determine flowfield structure and to investigate cause-and-effect with respect to the unsteadiness.

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Abstract

An exploratory investigation has been made of transitional shock wave boundary layer interactions. In this case, the interaction is induced by a circular cylinder perpendicular to a flat plate. The tests were conducted in the Mach 5 blowdown tunnel of The University of Texas at Austin. The primary goal of this initial, exploratory study was to determine if repeatable transitional interactions could be generated. Measurements included surface flow visualization using the kerosene-lampblack technique and high speed schlieren imaging. Consistent with earlier experiments the current work shows that as the cylinder is shifted upstream on the plate and the interaction start moves into an area where the incoming boundary layer is transitional, rather than turbulent, the separated flow and overall interaction scales increase significantly. The separation location moves from about 2 cylinder diameters upstream of the cylinder in turbulent flow to about 4 diameters in transitional flow. Tests made on different days with the cylinder at the same station on the plate, within the region of transitional boundary layer flow, are highly repeatable. This is a very promising result. With repeatability ensured from test to test techniques such as PIV can be used with confidence in future studies to determine flowfield structure and to investigate cause-and-effect with respect to the unsteadiness.

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1.0 Introduction

Shock wave/boundary layer interaction (SWBLI), often accompanied by separation, is a ubiquitous feature of high-speed flight. Most of the work done in the field over the past 50 years has been in fully turbulent flow because most of the applications have been at transonic and low supersonic speeds at altitudes where Reynolds numbers are large and turbulent flow the norm. Green[1], Korkegi[2], Stanewsky[3], and Hankey and Holden[4] provide reviews of the work up to the early 1970s. Later review articles by Delery and Marvin[5], Settles and Dolling[6], Dolling [7], Delery and Panaras[8], Zheltovodov[9], Smits and Dussage[10], and Knight and Degrez[11] cover work up until the mid to late 1990s. Experimental data discussed in these references acquired from blowdown, continuous and intermittent facilities at Mach numbers from transonic to hypersonic show that shock-induced turbulent separation is highly unsteady. Much of the work up until the early 1990's on the unsteadiness of separated turbulent flows has been reviewed by Dolling[7].

Transitional shock wave/boundary layer interactions, in which the incoming boundary layer is in a transitional state, or in which transition is induced within the interaction itself, have received little attention. The lack of attention has stemmed from both the lack of critical applications and from the formidable challenges that the study of such flows poses to both experiment and computation. The situation with respect to applications is now changing. High Mach number air-breathing propulsion systems are of increasing interest to the U S Air Force. The inlets of such air-breathing propulsion systems will have extremely complex shock/boundary layer interactions, with significant regions of transitional shock wave boundary layer interaction[12]. These transitional interactions will have a powerful influence on the local inlet flow properties and on the uniformity, the quality, and steadiness of the flow entering the combustor.

It is fair to say that our understanding of transitional interactions is extremely poor. The little knowledge we do have comes from old experiments and is largely qualitative. We do not know of any work done on simulating transitional interactions. Nor are we aware of any quantitative experimental data of the type needed to evaluate the predictions, and guide the effort. There is both a need, and an opportunity, to rectify the knowledge gap. The capabilities of modern non-intrusive instrumentation, especially PIV, and the rapidly evolving field of LES-based simulations make the next few years an ideal time to initiate studies of transitional interactions and build the knowledge base. As a first step in this direction the exploratory research program initiated under this grant provided funds to support a student to determine if repeatable transitional interactions could be generated in a Mach 5 blowdown tunnel. The results obtained are described briefly in this report.

2.0 Experiments

2.1 Exploratory Surface flow Visualization

In the initial phase of the experiment, an existing flat plate/circular cylinder arrangement was used, as shown in Fig. 1. In this experiment the cylinder was initially placed sufficiently far downstream of the plate leading edge (approximately 9 in.) such that the incoming boundary

layer at the upstream influence line was fully turbulent. This served as a reference case for comparison with data taken in previous studies using the same facility and with the large volume of work in turbulent flow from other facilities. Surface flow visualization using the standard kerosene-lampblack method indicated that separation at centerline occurred about 2.5D upstream of the cylinder, where D is the cylinder diameter. A sample kerosene-lampblack image of this case is shown in Fig. 2a, where the cylinder is located 9 inches from the leading edge. This result for the turbulent interaction is consistent with the recent work of Brusniak and Dolling[13], of Dolling and Smith[14], and of Westkaemper[15] in the 1960's and is typical of work in fully turbulent boundary layers from Mach numbers of 2 to 20. The cylinder was then progressively moved upstream on different runs such that the interaction was located in the transitional boundary layer. A sample image showing the cylinder approximately 3 inches upstream of the plate leading edge is shown in Fig. 2b. This figure shows that the separation line is considerably farther upstream of the cylinder than in Fig. 2a. At each station, the distance (S) between the separation location and the cylinder was determined. Figure 3 shows how S/D varies as a function of X, where X is the distance of the cylinder from the leading edge. It can be seen that as the interaction start shifts from being in the fully turbulent boundary layer flow to transitional flow, the separated flow scale increases rapidly, from about 2D to 4.4D. This observation is consistent with Chapman et al's work[17] in the late 1950's to the work of Young et al.[18] in the late 1960's.

In those initial experiments an extremely important consideration was to determine whether the results were repeatable from test-to-test, and from day-to-day. Experiments carried out during this phase of the work indicated that results were highly repeatable. The data were acquired over a period of several days with several repeat runs at selected locations. For example, tests were made on separate days at X = 4.5in and X = 4.1in. As can be seen from Fig. 3, the repeatability at these two stations is very good (better than about 4% at X = 4.5in and 2-3% at X = 4.1in).

In these exploratory tests the plate was secured in the tunnel from the sides using four pins in the tunnel sidewalls plus additional bolts. There was no need for a sting support between the tunnel floor and lower surface of the plate. The leading edge projected into the Mach 5 nozzle and the cylinder was shifted streamwise using a slider mechanism and secured in place using a ceiling brace. This arrangement, using existing hardware, was ideal for the initial flow visualization experiments but was not suitable for the next phase of the work, involving schlieren imaging. This was because the region on the plate over which transitional interactions occurred was upstream of the windows in the tunnel side-walls. Since the plate could not be shortened (the upstream pair of pins which held it in place were close to the leading edge) it was necessary to construct a new test plate for the imaging work.

2.2 "Imaging" Model Design

To optically access the interaction region, the plate had to be translated horizontally downstream to where the existing windows were available. Due to the size of the windows and the position of the upper surface of the plate relative to the window centers, the previous mounting mechanism with the pins at four corners could not be used, as noted above. Also the desire to visualize the boundary layer transition process and acquire images over a range of

cylinder positions required a plate that could be translated fore and aft relative to the stationary windows. These requirements called for an alternative supporting structure that used a floor strut. In addition the plate length was reduced to 10 inches. A longer plate was unnecessary since the exploratory work had shown that all the interactions of interest occurred over the first few inches of the plate. A length of 10 inches provided room for a cylinder translation mechanism and also ensured that any trailing edge wake or strut wake unsteadiness would not be felt upstream.

2.3 Tests and Subsequent Model Modifications

Although the initial plate/strut model would not allow the tunnel to start, the issue of tunnel blockage initially seemed resolved when the strut width was reduced by 1/4 inch on both sides. At that stage, the tunnel instrumentation indicated steady Mach 5 flow at the nozzle exit, even though it was noted that the final tunnel controller settings were outside of the normal operating parameters. However, once schlieren imaging was performed, it was clear why the latter was the case.

Examination of schlieren images showed the presence of an oblique shock emanating from the tunnel ceiling and intersecting the cylinder bow shock. It was thought originally that the interaction between the thick ceiling boundary layer and the ceiling brace caused separation on the ceiling. To investigate this further, the ceiling brace was eliminated by modifying the plate so that the cylinder could be screwed into it, providing a clearance of 1 inch between the ceiling and the cylinder. Since the ceiling boundary layer is approximately 0.7 in thick, the top of the cylinder would be in the tunnel freestream flow.

Schlieren imaging was again performed and it was found that the oblique shock was still present. The leading edge region of the plate was then imaged and revealed that there was an oblique shock system present in the tunnel, caused by blockage both below and above the plate. The complex 3-D shock system produced by the 12 degree horizontal plate leading edge in conjunction with the shocks from the 12 degree leading edge of the vertical strut resulted in a high enough back pressure to cause the shock to move upstream of the plate. Further, it was also shown that the cylinder itself was partially to blame for the blockage since the tunnel started without the cylinder present.

To solve this problem, the first step was to reduce the strength of the cylinder bow shock and reduce the strut dimensions. The cylinder was first reduced to 1.125 *in* high with no apparent change in the oblique shock. The strut width was reduced to 0.55 *in* thick with the same results. Another cylinder with diameter of 1/4 *in* and height of 1 *in* was then used. This resulted in an intermittent oblique shock at the cylinder's position indicating that the tunnel was starting only intermittently.

The final solution was to reduce the height of the 1/4 *in* cylinder to the minimum of two diameters (1/2 inch), streamline the rear of the strut and machine away part of the lower surface of the plate. The plate thickness was reduced 0.2 *in* to 0.5 *in* on the sides flanking the strut support. Also the trailing edge was boat-tailed with a 12-degree angle. The combination of

these changes resulted in successful tunnel start. The Schlieren images show a Mach wave of 12 degrees corresponding to Mach 5 flow at the leading edge and a steady cylinder bowshock.

3.0 Summary

The surface flow visualization studies showed that repeatable transitional interactions can be generated in our Mach 5 wind tunnel. However, attempts to visualize the transitional interactions proved to be problematic because the new plate-model that was designed for this purpose included a strut that provided too much blockage and therefore gave problems starting the tunnel. With hindsight this design was a mistake and future experiments will be conducted using a custom-built plate, pinned at the sides, and with inserts for imaging. High-speed schlieren imaging (9000 frames per second) was shown to be useful for diagnosing the tunnel starting problems and should prove critical to future studies of transitional interactions since details of the time-dependant flow structure can be obtained. Despite the problem with the second model, this exploratory study has demonstrated that studying transitional interaction is feasible and that, given appropriate resources, much can be learned of the basic physics of these flowfields.

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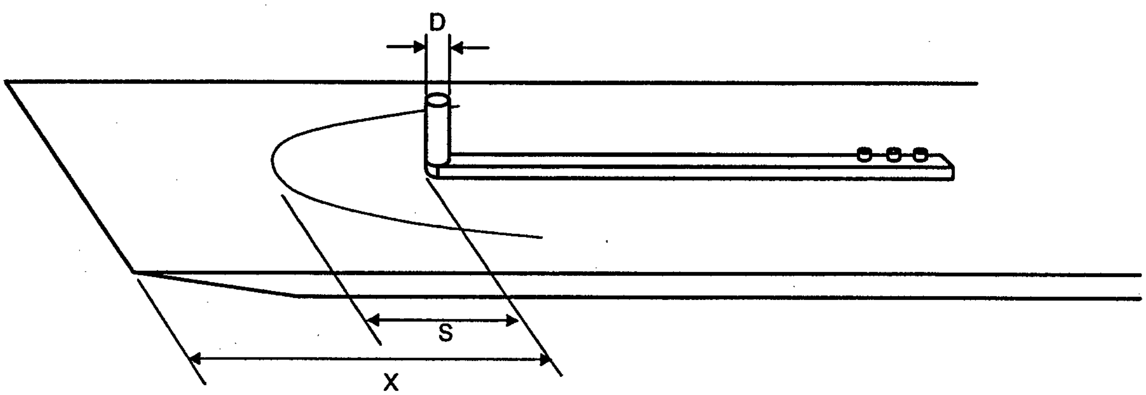
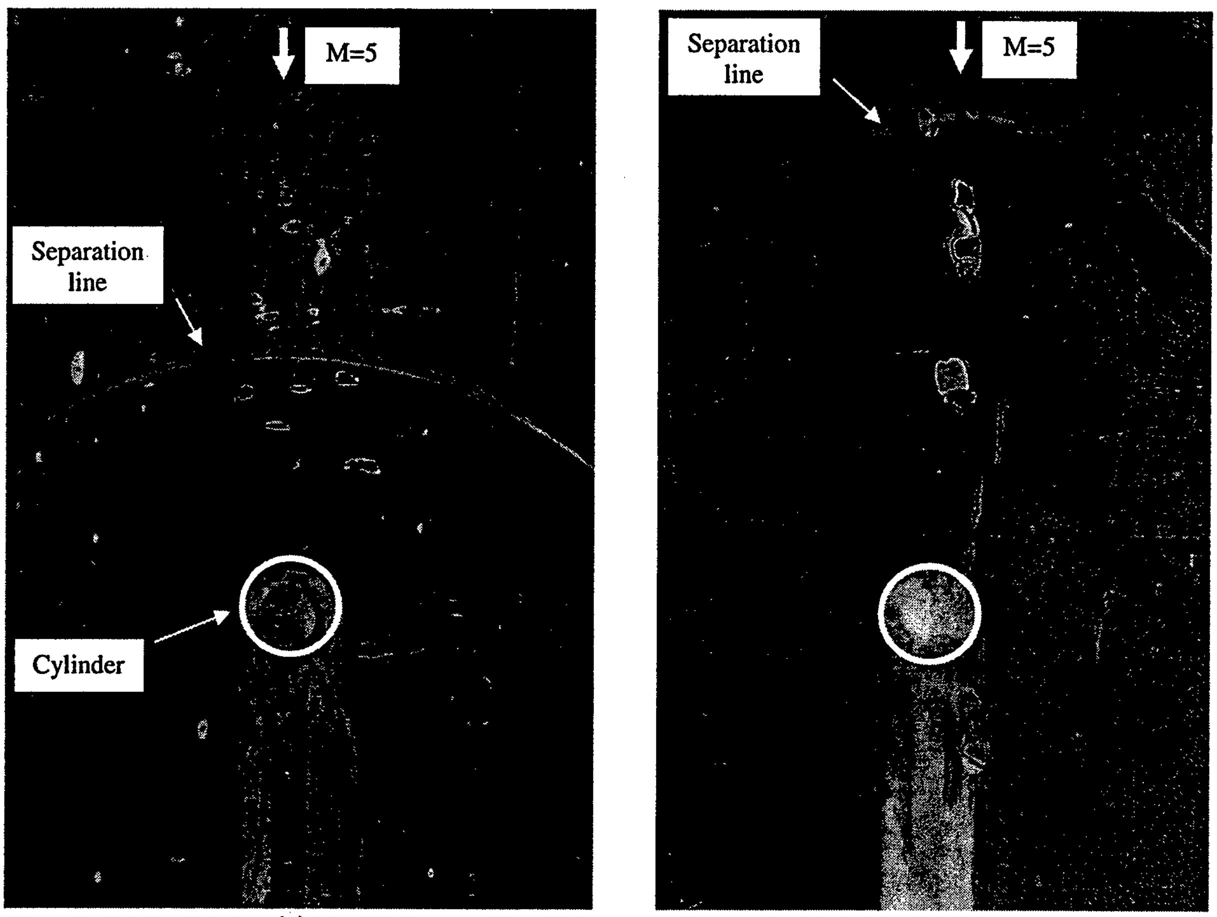


Figure 1. Schematic of the experimental setup for the surface flow visualization experiments. S is the distance of the separation line (at centerline) to the cylinder. X is the distance between the cylinder and the leading edge.



(a) (b)

Figure 2. Sample kerosene-lampblack surface flow visualization images. The flow is from top to bottom. (a) Cylinder placed 9 inches from the plate leading edge, (b) cylinder placed 3 inches from the plate leading edge.

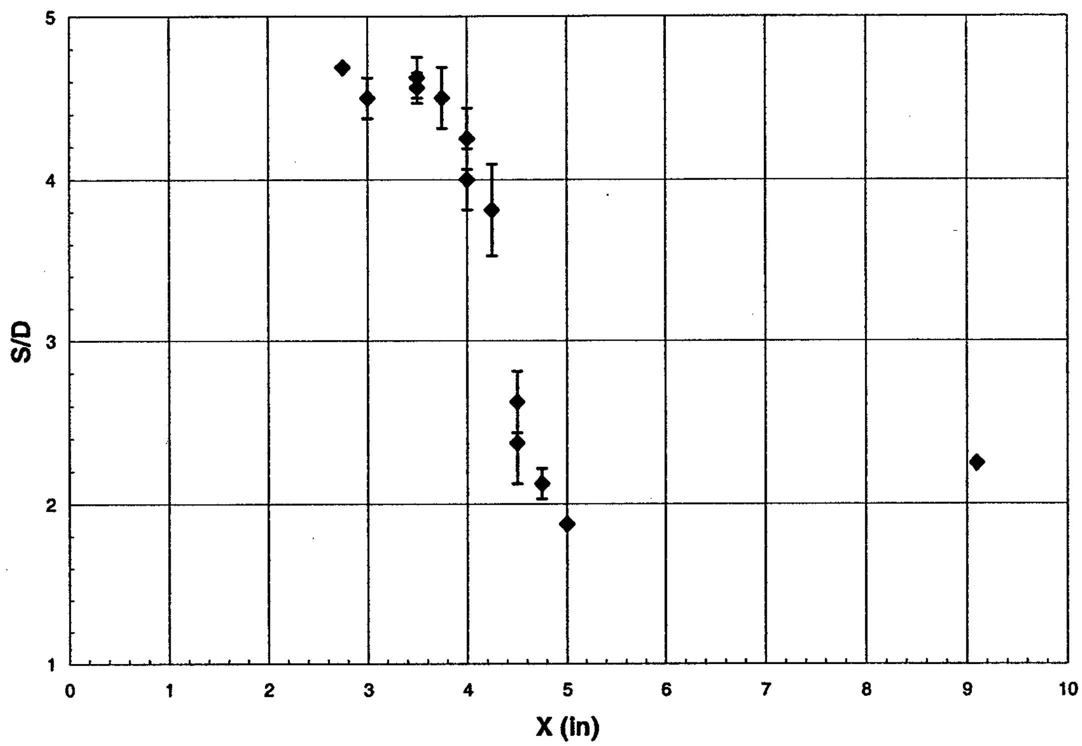


Figure 3. Variation of S/D as a function of the distance of the cylinder from the plate leading edge (X).